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ECOM- 01698-8

LONG-LIFE COLD CATHODE STUDIES FOR CROSSED-FIELD TUBES

PROGRESS REPORT

by

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C. McGeoch

FEBRUARY 1968

Contract DA28-043-AMC-01698 (E)

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RAYTHEON COMPANY
MICROWAVE AND POWER TUBE DIVISION
Waltham, Massachusetts

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Eighth Quarterly Report

15 July to 15 October, 1967

Report No. 8
Contract No. DA28-043-AMC-01698(E)
DA Project No. 7900-21-223-12-00

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For

U. S. Army Electronics Command
Fort Monmouth, N. J. 07703

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ABSTRACT

A machined 6061 (97.5% purity) aluminum target, a machined 1100 (99.0+% purity) aluminum target, and a 9500 Å aluminum layer on copper target were each evaluated in the Electron Bombardment Vehicle for approximately 40 hours under high current density electron bombardment conditions, both with and without oxygen. δ_{max} varied between 1.5 and 2.5 for the two machined aluminum samples and between 1.5 and 2.8 for the evaporated aluminum target.

The evaporated aluminum sample showed more consistent performance as well as more rapid recovery under electron bombardment in the presence of O_2 than did the machined aluminum samples. Possible correlation with surface strains and defects is suggested.

A successful 1000 hour life test of a beryllium cold cathode with a partial pressure of O_2 was performed in a QKS1267, a 3 GHz, 1.6 kW CFA under a separate program.

Initial test processing of QKS1397 Model No. 8B with an aluminum cathode was performed and the tube awaits life test. The QKS1194 CFA test vehicle with impregnated tungsten emitter was tested for 10 hours. A life-test operating point at a one-megawatt power level was established and the tube is awaiting life test.

FOREWORD

Long-life cold cathode studies for crossed-field tubes are authorized by the United States Army Electronics Command, Fort Monmouth, New Jersey, under LA Project No. 7900-21-223-12-00. The work was prepared under the support of the Advanced Research Projects Agency under Order No. 345 and is conducted under the technical guidance of the U. S. Army Electronics Command, Fort Monmouth, N. J. 07703.

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1. INTRODUCTION

The objective of the present cold cathode study program is to achieve long life cold cathode performance for crossed-field amplifiers. This program is being performed for the United States Army Electronics Command, Fort Monmouth, New Jersey, under contract DA-28-043-AMC-01698 (E).

In this study, selected cold cathode materials will be evaluated as to: their secondary emission properties, their ability to withstand environmental factors expected in a crossed-field amplifier, and their crossed-field amplifier performance. Based on the above experimental information and pertinent theoretical calculations, a life prediction chart will be established for a number of cold cathode materials.

The program is divided into two concurrent phases, Phase A being concerned with the measurement of various pertinent properties of cold cathode materials outside of the tube environment, and Phase B involving the evaluation and life testing of selected cathodes in a crossed-field amplifier.

The first quarterly report of this contract (Technical Report ECOM 01698-1) contains a discussion of the objectives and plans for the over-all program. Quarterly report no. 5 contains a description of the CFA test vehicles used in this program.

2. PHASE A - MATERIALS EVALUATION

2.1 Secondary Emission Measurements. As a continuation of last quarter's effort, a second set of barium calcium aluminate impregnated tungsten samples were prepared having varying impregnant composition and porosity. The purpose of this experiment was to assess the relative significance of the secondary emission property of the impregnant oxides and of the tungsten surfaces, with or without Ba coverage.

Seven samples were installed in the Secondary Emission Test Vehicle (SEE) and δ measurements were made as a function of primary electron energy. The measured values of δ_{max} at various stages of activation are tabulated below.

The lack of consistency among samples prevents any significant correlation with porosity and impregnant composition. The general trend of δ (as noted in our previous measurements) is that it increases as a result of system bakeout and initial activation and subsequently decreases on further activation. After system bakeout, the high porosity (HP) samples had a slightly higher value of δ_{max} than did the low porosity (LP) samples. One would expect the δ of the impregnant material (oxides) to be larger than that of tungsten. After the 1 hour activation at 1100°C the HP samples had δ values equal to or less than those of the LP samples. It may be that the activation of the tungsten surface by barium contributes significantly to the overall secondary emission value.

TABLE I

δ_{max} of Barium Calcium Aluminate Impregnated Tungsten at Various Stages of Activation

Sample No.	Porosity (%)	Impregnant Composition*	δ_{max} Before Bakeout	After Bakeout**	1 hr 1100°C Activation	Additional 1/2 hr 1100°C
S1	20	4:1:1	2.0	2.3	4.0	---
S2	20	2:1:1	2.1	2.0	4.0	---
S3	20	2:1:1	2.4	2.4	4.3	---
S4	34	2:1:1	2.3	2.7	4.1	3.4
S5	34	2:1:1	2.6	2.6	3.1	2.7
S6	34	4:1:1	2.3	2.4	2.8	2.9
S7	34	4:1:1	2.0	2.4	4.4	3.4

* 4:1:1 denotes molar composition of $BaCO_3$, $CaCO_3$, and Al_2O_3 respectively.

** Overnight at 400°C

The missing measurements for the LP samples in the above table, after the additional 1/2 hour of activation, are due to the loosening of the samples under the setscrew and their rotation out of position.

A typical plot of δ vs primary electron energy in Figure 1 shows quite normal behavior. A similar plot was obtained for each sample quoted in the table.

It is planned to repolish these samples, thus revealing a fresh surface, and to remeasure them in the SEE test vehicle.

2.2 Electron Bombardment Evaluation. During the present quarter, the work on electron bombardment evaluation consisted of

1. Construction of additional electron bombardment test vehicles and some modification of existing ones.

2. Evaluation of three Al_2O_3 on Al samples formed by room-temperature air oxidation:

   a. 6061 Al (97.5% Al)
   b. 1100 Al (99.0+% Al)
   c. 9500 Å Al film deposited on copper

3. Preparation of a variety of Al and Be samples for EBV evaluation.

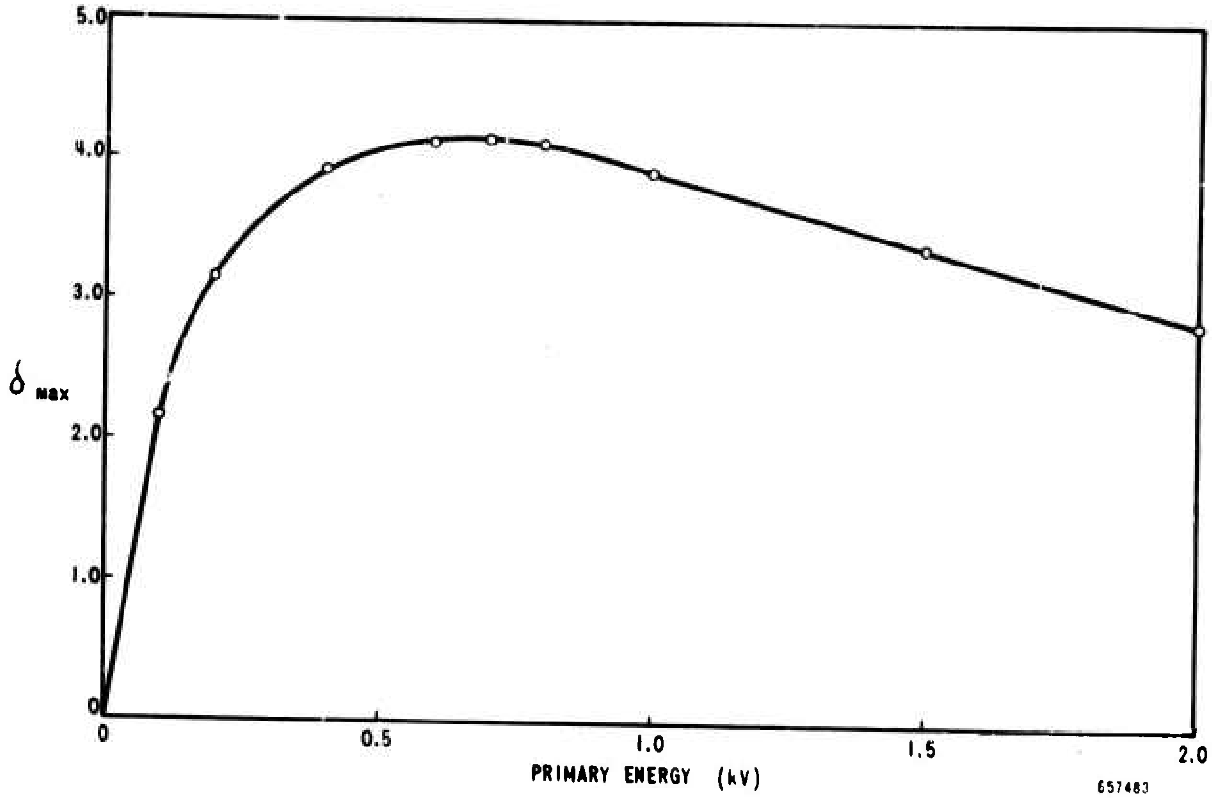

Figure 1. Secondary Emission Ratio vs Primary Energy for Impregnated Tungsten Sample

2.2.1 Electron Bombardment Vehicle (EBV) Testing of Three Al_2O_3 on Al Samples.

2.2.1.1 1100 Aluminum. A machined, chemically cleaned target of 1100 aluminum (99.0+% purity) was evaluated in the EBV during a 43-hour period. The results are shown in Figure 2 in which δ_{max} is plotted as a function of EBV time. The numbers shown above the curve indicate the level of electron bombardment of the target in milliamperes, 10 ma corresponding to 0.5 Amp/cm^2. The letter N appearing below the curve indicates that the target potential was negative relative to the anode potential although both are above gun cathode potential. The gaps in the curve indicate periods during which the EBV was completely shut off (usually overnight). During periods of zero bombardment (as indicated above the curve) the cathode of the electron gun was at its emitting temperature. The residual vacuum (with the O_2 source off) during EBV operation was typically 2-5 x 10^{-8} Torr. δ_{max} varied between 1.4 and 2.5. Electron bombardment with the O_2 source off always caused δ to decrease. Although previous measurements in this program have usually indicated that the presence of O_2 would result in an increase in δ, particularly with electron bombardment of the target in the negative sense (target negative relative to anode), the present data (see hours 24-30 on Figure 2b) showed δ to decrease under such conditions. Again, as observed on previous occasions, off-periods usually resulted in increases in δ, although sometimes it decreased. As will be noted below, inconsistencies in the data for this sample as well as for other machined aluminum samples, are believed to be associated with surface strain and defects characteristic of machined surfaces.

2.2.1.2 6061 Aluminum. A machined, chemically cleaned target of 6061 aluminum (97.5% purity) was evaluated for 37 hrs in the EBV. The results are shown in Figure 3. δ_{max} varied between 1.5 and 2.5. Under 1 Amp/cm^2 bombardment, δ_{max} appeared to hold at about 1.5 (see hours 18-30). The attempt to increase δ by the use of O_2, starting with hour 31, was not particularly successful. With 3 ma bombardment in the negative sense and in the presence of O_2 at a pressure of 7 x 10^{-6} Torr, δ_{max} increased only slightly in comparison with the results for the evaporated aluminum layer (see Figure 4 below).

2.2.1.3 9500 Å Evaporated Aluminum Layer on Copper. A 9500 Å thick evaporated aluminum layer was deposited on an OFHC polished copper substrate and evaluated in the EBV during a 40 hour period. Figure 4 shows the behavior of δ_{max} during this period. The results on this sample appear more consistent than did those of the machined aluminum samples. Changes during overnight off-periods were smaller than for the machined samples. Rapid recovery of δ was observed under electron bombardment in the negative sense in the presence of oxygen. The value of δ_{max} varied between 1.5 and 2.8 for this sample. The minimum value of δ_{max} was approximately 1.5, as it was for the two machined aluminum samples reported in this quarterly period. Electron bombardment in both the positive and negative sense (3 ma level) gave similar rates of recovery of δ. This rate was of the order of 5 times as large as the recovery without bombardment, with oxygen present in both cases. The above results suggest the beneficial effect of increased temperature (due to electron bombardment) on reoxidation of the aluminum. The more consistent results, as well as the improved recovery

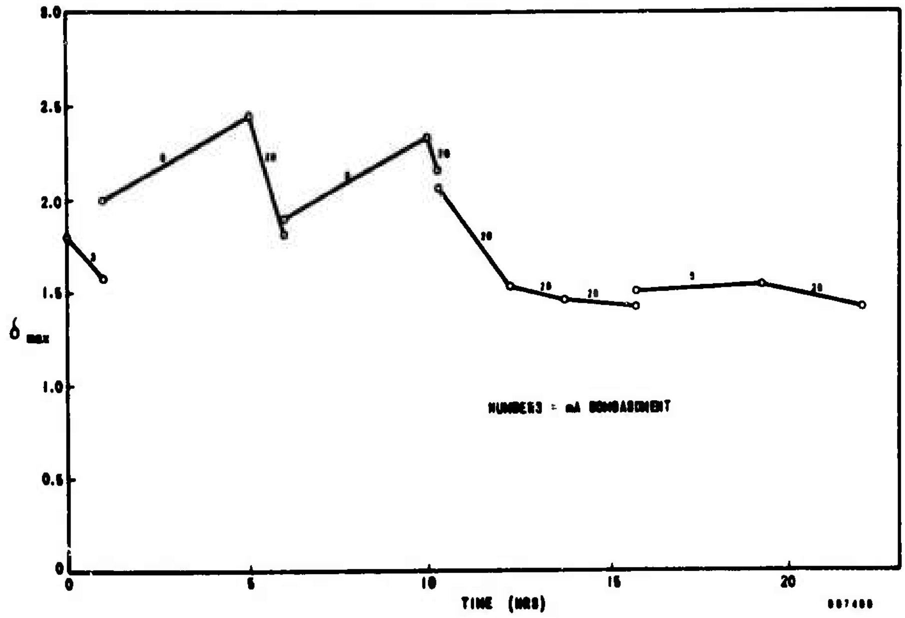

Figure 2a. δ_{max} vs EBV Time for 1100 Aluminum

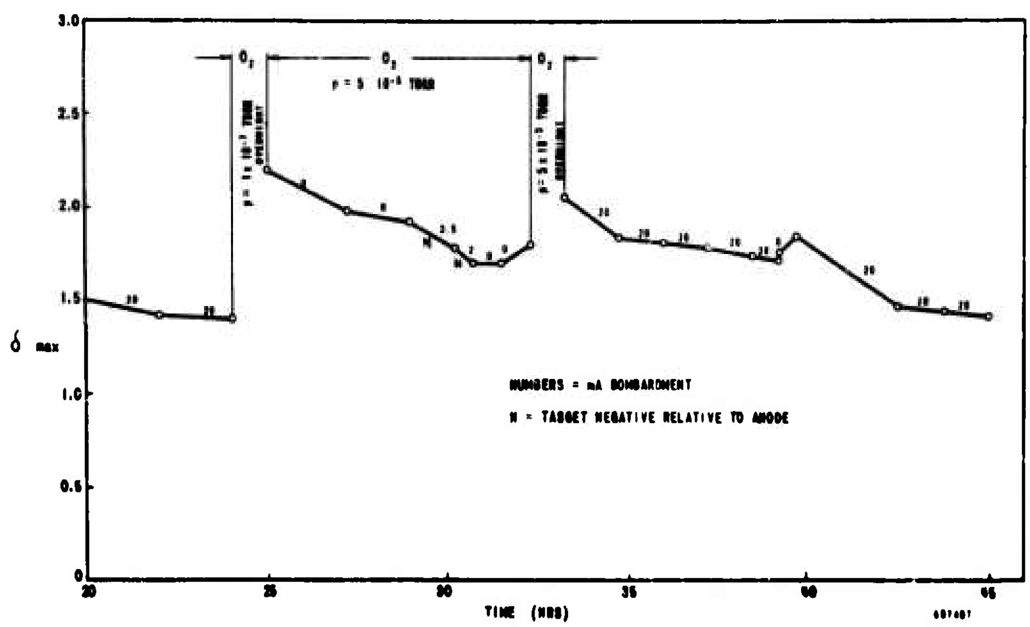

Figure 2b. δ_{max} vs EBV Time for 1100 Aluminum

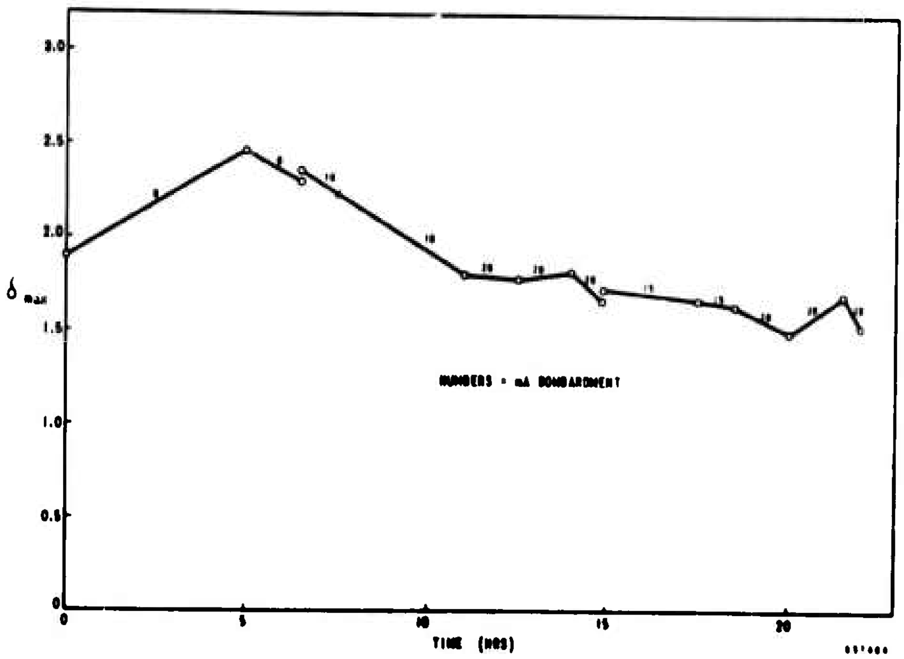

Figure 3a. δ_{max} vs EBV Time for 6061 Aluminum

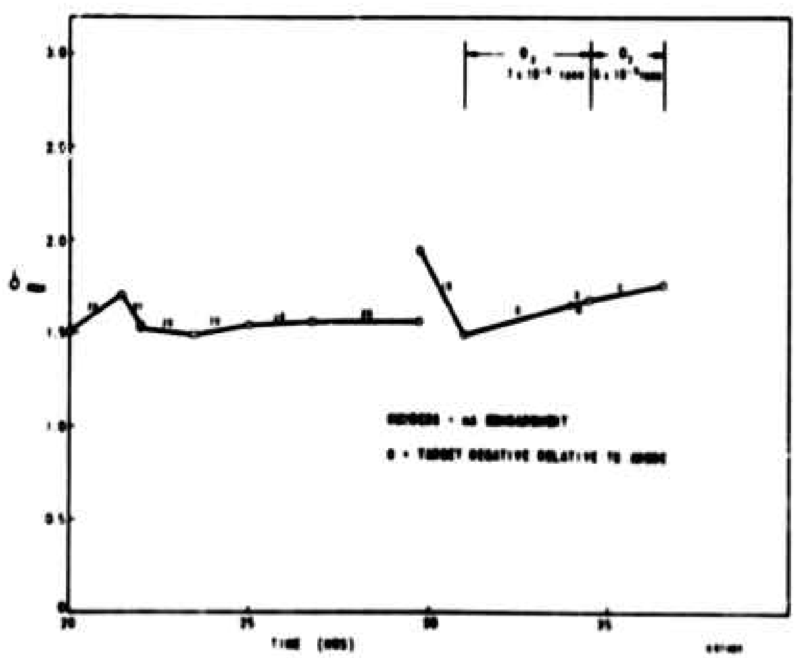

Figure 3b. δ_{max} vs EBV Time for 6061 Aluminum

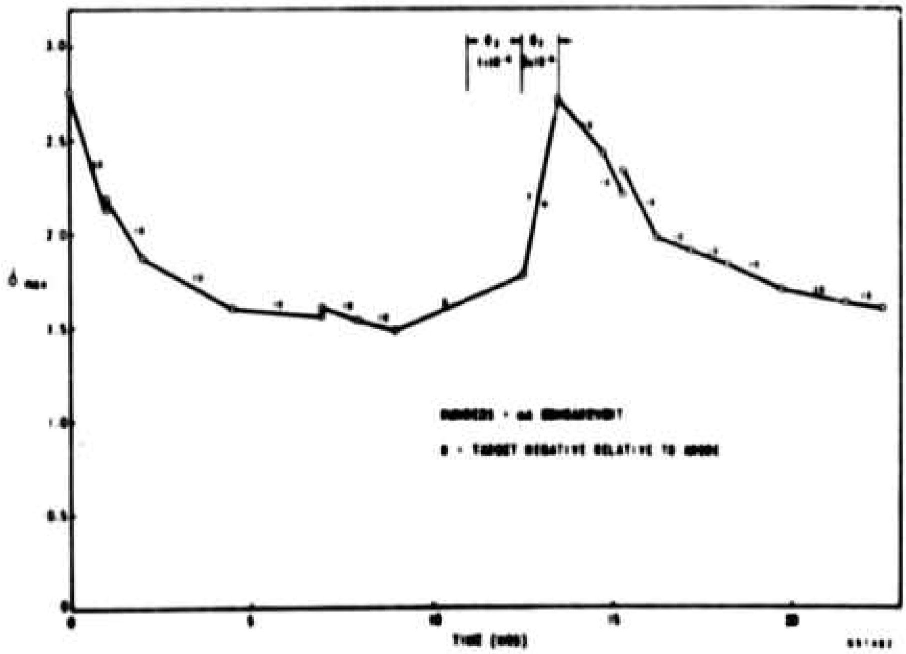

Figure 4a. δ_{max} vs EBV Time for 9500 Å Evaporated Aluminum on Copper

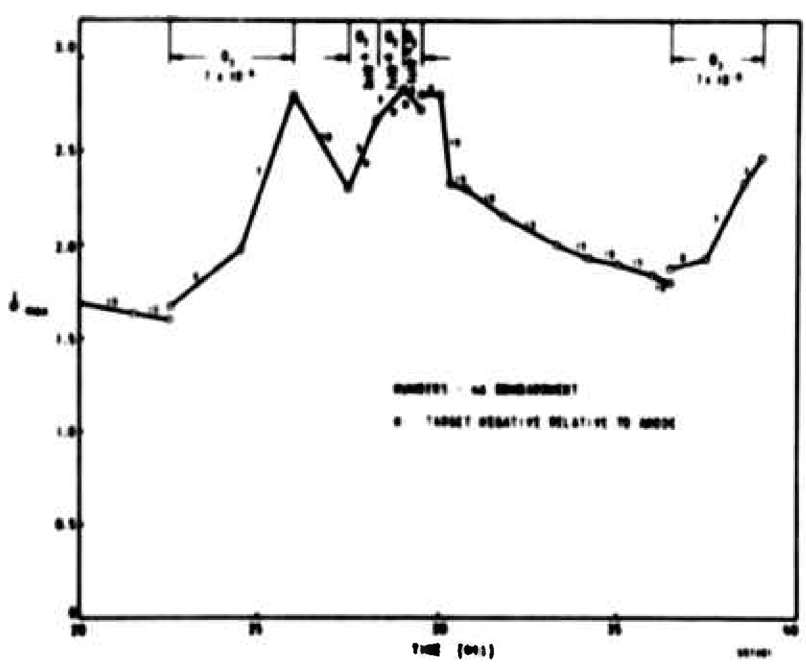

Figure 4b. δ_{max} vs EBV Time for 9500 Å Evaporated Aluminum on Copper

rates for this sample as compared with machined aluminum, suggest the role of surface strain and defects probably present in the machined samples.

2.2.2 EBV Construction and Modification. Additional EBV's have been constructed during the present quarter in order to achieve steady 2-vehicle operation. The complete EBV consists of a gun assembly and a target assembly bolted to each other. Three new gun assemblies have been completed while two more are partially assembled. In addition, 4 new target assemblies of improved mechanical and thermal design have been partially completed.

2.2.3 High Stress EBV. During the present quarter further work was done on diffusion bonding of an aluminum-to-copper disc. Two successful 'onds were made at 500°C for 30 minutes. One of these samples was sectioned and polished. It showed a thin region, probably consisting of an intermetallic compound of aluminum and copper, with interdiffusion solid-solution regions on either side.

2.2.4 Sample Preparation. The following samples were prepared during this quarter:

1. 3 new impregnated tungsten samples for the hot-cold EBV.
2. 4 - 6061 Al samples for cold EBV.
3. 4 - 1100 Al samples for cold EBV.
4. 4 - 9500Å evaporated Al on Cu.

In addition the following samples are partially completed:

1. 4 Be samples (to be diffusion bonded to Cu) for cold EBV.
2. Electron-bombardment-evaporated Al_2O_3 layer on molybdenum substrate.

It is planned to anodically oxidize the Al and Be samples to a thickness of approximately 300Å. Oxide layers thus formed may be relatively porous or non-porous, depending on the extent to which the anodizing solution dissolves the oxide as it is formed. It is planned to use two different anodic baths in order to achieve a porous and a non-porous oxide layer. According to Wargo and Shepherd[1] the dissociated oxygen released through the surface probably diffuses through pores, since the dissociation kinetics cannot be accounted for by the bulk diffusion rates.

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[1] P. Wargo and W. G. Shepherd - Electron-Bombardment-Induced Dissociation of Alkaline Earth Oxides. Phys Rev. 106, 694 (1957).

3. PHASE B - CFA TESTING

3.1 Introduction. During this quarterly period, operating data was obtained with three different oxide-film, secondary-emission cathodes (beryllium, aluminum, and impregnated tungsten) in different CFA vehicles. The secondary yield (effective δ) of this class of emitter is from 2.2 to 5.0 or more, considerably higher than the 1.8 - 1.9 peak value available from platinum; the yield of the oxide film is also higher than that of platinum at the low energy levels which are encountered in CFA's designed to operate at low voltages or with low rf drive levels. Because of the apparent superiority of this class of emitter for many high performance CFA designs, the conditions under which oxygen can be administered to them to secure prolonged operating life are being studied. Each of the cathode evaluation CFA vehicles described in the following sections was built with a small oxygen dispenser operating with a nominal 40-60 watts from a low voltage ac power supply at ground potential.

3.2 Test of Beryllium Oxide Emitter for 1000 Hours in QKS1267. Life test information was accumulated during the interim on a cold beryllium oxide cathode operating in a special model of the QKS1267 Amplitron. While not specifically planned as part of this program, the results are reported here because of their direct relation to the goals of the Cold Cathode Study. The tube was built as a means of avoiding a difficult heater problem in the normal thermionic cathode which arose for an application requiring the tube to operate at both a very low and a very high duty cycle.

A beryllium emitter sleeve was installed in the QKS1267, in place of the regular emitter; an oxygen dispenser was also incorporated in the tube. Both emitter and oxygen dispenser were of the same types as those which have been used in several Raytheon forward-wave CFA types including the QKS1319 (L-band) and QKS1397 (S-band). The tube was processed and tested normally. It was established that the oxygen dispenser required about 5.0 volts and 7.0 amperes ac to maintain stable emission of the tube for more than short periods. This value of dispenser was specified for operation in the customer's transmitter. Operation at 3.5 amperes peak, the normal current for the tube's rated 60 kW (peak) output, was maintained uneventfully for 274 hours. It then became necessary to raise the applied dispenser voltage to 5.5 volts to counteract a decreasing emission limit - only 2.8 amperes peak over part of the specified 2.9 - 3.1 GHz band. This change rapidly increased the emission to normal and the test was continued without any trouble attributed by the customer to the Amplitron for a total of 1000 hours.

The 1000 hour test was operated 16 hours per day on 5 and 6 day work weeks with frequency changed 10 MHz every hour and power measurement made every 4 hours. The operating point was:

e_b = 27 kV (cathode pulsed)

i_b = 3.5 amperes peak

I_b = 95 mA

t_p = 34 microseconds

PRR = 800

Du = .027

p_o = 60 kW peak

P_o = 1.620 kW average

p_d = 1.6 kW peak

f = 2.9 - 3.1 GHz

No performance deterioration was observed during or after the test. The cold cathode emitter stress levels were as follows:

Average Current Density:	15.2 mA/cm^2
Peak Current Density:	0.56 a/cm^2
Average Power Dissipation Density:	30 W/cm^2

The average current and power dissipation levels in the QKS1267 are close to those required in the QKS1397 forward-wave CFA Cold Cathode Study test vehicle at the 5000 watt average power output level (22 mA/cm^2 and 37 W/cm^2, respectively). The peak current density of the QKS1397 (4.5 a/cm^2) and other high peak power CFA's is greater than that in the QKS1267, however, both peak and average back bombardment current densities are probably significant to cold emitter life. It is true that the effective secondary yield, δ, required of the QKS1267 emitter is low (δ_{eff} = 1.4) compared to that required of the QKS1397 emitter (δ_{eff} = 3.4 for 1 MW, 2.2 for 0.5 MW) because of the low peak operating current. For another reason, however, the QKS1267 requires very good secondary emission not available from a platinum cathode. This is the low unity-δ crossover energy required to provide reliable jitter-free rf starting at the 1.6 kilowatt peak rf drive level specified for the tube. No trouble was experienced with rf starting throughout the 1000 hour QKS1267 operating test.

The QKS1267 1000-hour test is believed to be significant in establishing that oxygen-stabilized cold cathode emission can be achieved from an oxide-film secondary emitter cathode in a moderately high average power CFA environment. Although additional data of this sort is required and will be sought on this program using the QKS1397 CFA vehicle, it is believed that the oxide film emitter with oxygen dispenser represents a practical design which can be applied to many CFA's.

3.3 Tests with QKS1397 Test Vehicle. The QKS1397 Life Test Vehicle with aluminum cathode and oxygen dispenser has been evaluated at hot test and subjected to a steady test run of several hours duration. Anode characteristics show that considerable leakage current is present, accounting for sub-normal efficiency of about 30% at the megawatt output level. Nevertheless, copious emission is available and can be maintained with the use of oxygen. The performance of the model is considered adequate to provide representative data on the oxide film operating life at a moderately high stress level. It is planned to run this cathode-pulsed emitter test for a period of 100 to 200 hours, or until the character of any deterioration is defined. This testing is scheduled for the next quarterly interim when best modulator drive is expected to be available. The following operating point has been selected for this testing.

$$f = 3.4 \text{ GHz}$$

$$p_o = 877 \text{ kW peak}$$

$$P_o = 1770 \text{ W average}$$

$$i_b = 100 \text{ amperes peak}$$

$$e_b = 28 \text{ kilovolts}$$

Operating parameters will be recorded, and the maximum available emission current (peak) at full magnetic field and at reduced field will be monitored periodically. Effort will be made to maintain the partial pressure of oxygen in the tube at a level consistent with stable operation and long life. It will be determined if this can be accomplished at a fixed value of oxygen dispenser heater power.

The QKS1397 Test Vehicle will be reconstructed with the most stable aluminum oxide emitter surface available at the time the present vehicle has completed its test run. It will incorporate any changes which the present test predicts to be necessary for long life. It is planned to operate the reconstructed test vehicle for a prolonged period of over 1000 hours.

3.4 Test of QKS1194 with Impregnated Tungsten Emitter. The QKS1194 test vehicle with the barium calcium aluminate impregnated tungsten cathode was set up in the final amplifier position of an S-band chain system. This tube was evaluated previously and the test results were included in quarterly report No. 6.

The tube was operated cold cathode at 1 MW peak power output to age it in over the band. Previous testing had been performed at a single frequency. Low gauss emission-current boundary data were taken and indicated no deterioration in emission. Calculations confirm the original δ of 3.5 as previously reported.

An operating point was established for life testing at high peak power output. The test vehicle produced stable power out at the following set of operating conditions:

e_b (anode voltage)	- 46 kV
I_b (average anode current)	- 650 ma
i_b (peak anode current)	- 36.1 amps
t_p (pulse width)	- 80 μsec
du (duty cycle)	- .018
P_o (average power)	- 22.5 kW
p_o (peak power)	- 1.25 MW
gain	- 13 dB

Life test operation at this point represents an average cathode stress level of 29.1 ma per cm^2 or peak current density of 1.6 amp per cm^2.

The test vehicle will experience 100 hours life testing with frequent time interval low gauss e.c.b. data checks during the next quarter.

Since this tube has an internal oxygen source and the heatable-coolable feature for the cathode, further tube evaluation of these parameters will be performed as dictated by tube performance.

4. CONCLUSIONS

4.1 Phase A. A 9500Å evaporated aluminum-on-copper target showed more consistent performance as well as more rapid recovery under electron bombardment in the presence of oxygen than did the machined aluminum samples. Possible correlation with surface strain and defects is suggested.

4.2 Phase B. A successful 1000 hour life test of a beryllium cold cathode, with a partial pressure of oxygen, was performed in a QKS1267 backward wave CFA under a separate program. This represents a significant demonstration of the feasibility of this approach.

5. PROGRAM FOR NEXT INTERVAL

5.1 Phase A

1. Continue testing of oxidized aluminum and beryllium targets in EBV.

2. Evaluation of Ni cermet and/or impregnated tungsten samples in hot/cold EBV.

5.2 Phase B

1. Continue evaluation and life testing of the QKS1397 CFA with aluminum cathode and oxygen dispenser.

2. Continue evaluation and life testing of the QKS1194 CFA with impregnated tungsten emitter, an oxygen dispenser, and a heatable-coolable cathode structure.

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Initial test processing of QKS1397 Model No. 8B with an aluminum cathode was performed and the tube awaits life test. The QKS1194 CFA test vehicle with impregnated tungsten emitter was tested for 10 hours. A life-test operating point at a one-megawatt power level was established and the tube is awaiting life test.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Cold Cathode						
Crossed-Field Amplifiers						
Electron Bombardment						
Ion Bombardment						
Thin Films						
Aluminum Oxide						
Beryllium Oxide						

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